Manley 19

ERID 011714

STRATIGRAPHY AND STRUCTURE OF THE ESPAÑOLA BASIN, RIO GRANDE RIFT, NEW MEXICO

Kim Manley

U.S. Geological Survey
Branch of Central Environmental Geology, MS 913
Box 25046, Federal Center
Denver, CO 80225

Abstract. The Española basin, part of the Rio Grande rift in northern New Mexico, contains sedimentary and volcanic rocks of Eocene to Quaternary age. The onset of rifting, based on evidence from north and south of the basin, is generally considered middle to late Oligocene. Deposits of late Oligocene and early Miocene age extend beyond the margins of the present basin, offering no evidence that boundary faults existed at that time. The basin was probably a shallow depression between the eastward-tilting Nacimiento uplift and the westward-tilting Sangre de Cristo Mountains. Extensional faulting and volcanism near the western basin margin began in mid-Miocene time. Mid-Miocene to Pliocene rocks lap onto the Precambrian rocks of the Sangre de Cristo Mountains and have minor offsets along late Miocene to Pliocene faults.

The northeast-trending Velarde graben, with stratigraphic offset of as much as 360 m, formed in the central Española basin in early Pliocene time. The western side of the graben is partially bounded by the Pajarito fault zone, along which the Quaternary Bandelier Tuff has been offset. Early Pliocene deformation waned about 4 m.y. ago. A series of broad penecontemporaneous surfaces were cut across older basin-fill deposits; one of these is the Ortiz surface in the Santo Domingo subbasin. Overlying these surfaces are several formations 2.9 to 2.0 m.y. old. The Rio Grande was apparently established in conjunction with the Pliocene erosion. Volcanic activity in the Cerros del Rio field 3 to 2 m.y. ago periodically dammed the river, which downcut in the late Quaternary until the present topographic Española basin was formed.

Introduction

Using considerable new data, this paper summarizes the known Cenozoic history of the Española basin; it also calls attention to areas requiring further study.

The Española basin is one of many Cenozoic structural and topographic basins, aligned north-south from central Colorado to southern New Mexico, that constitute the Rio Grande rift (Chapin, 1971; Chapin and Seager, 1975) (fig. 1). The Española basin is 40 km long and 65 km wide (fig. 2). Structurally, the basin is separated from the Santo Domingo subbasin to the south by the northwest-trending La Bajada fault which has displacement down to the southwest. To the north, the Española basin is separated from the Taos Plateau and San Luis basin by a basement ridge (Cordell, 1978) extending northwest from the Picuris Range through an isolated Precambrian exposure at Cerro Azul to the La Madera area. The Española basin is bounded by the Precambrian-cored Nacimiento uplift on the west and the Sangre de Cristo Mountains on the east.

The western half of the basin is filled with volcanic rocks of the

7314

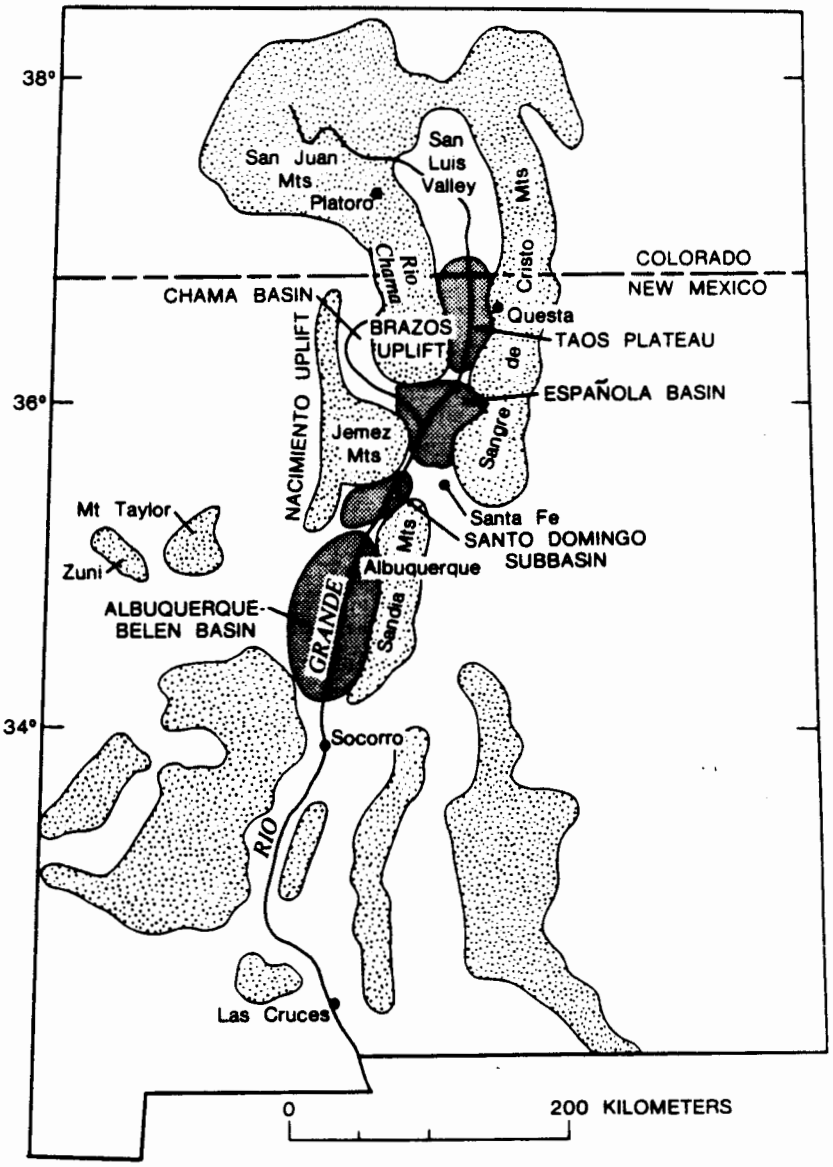

Fig. 1. Regional map of New Mexico and southern Colorado.

Jemez Mountains, which define the western edge of the topographic basin. North and south, the basin terminates near basalts of the Servilleta Formation and Cerros del Rio volcanic field, respectively. Tertiary sedimentary rocks and several Pliocene-Pleistocene alluvial deposits are preserved in the central basin and the Picuris and Abiquiu reentrants.

Previous Work

Cenozoic sediments in the east-central Española basin have been described by Galusha and Blick (1971); in the northeastern portion, by Miller and others (1963) and Manley (1974, 1976a, 1976c); and in the southern portion, by Spiegel and Baldwin (1963) and Manley (1976a, 1976b). The Cerros del Rio volcanic field has been studied by Griggs

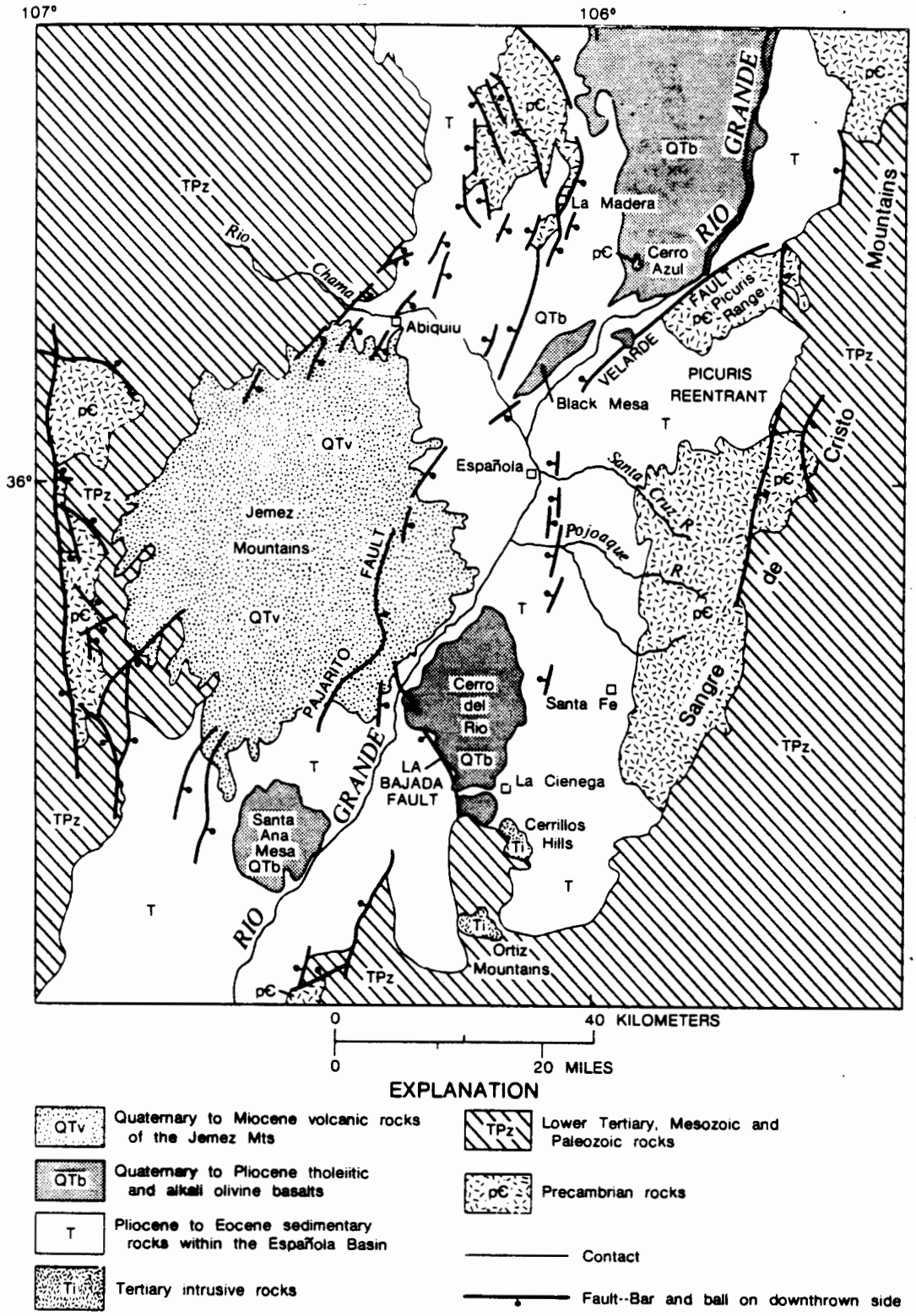

Fig. 2. General geologic map of the Española basin, New Mexico.

(1964) and Aubele (1978); and the Jemez Mountains, by Griggs (1964), Bailey and others (1969), and Smith and others (1970). K-Ar ages for the Cerros del Rio volcanic field are given by Manley (1976b) and Bachman and Mehnert (1978). Fission-track ages of tephra layers in Santa Fe Group are in Manley (1976a) and Manley and Naeser (1977).

Stratigraphy

Pertinent aspects of the stratigraphy are discussed here to document the geologic history (fig. 3). The deposits of earliest Tertiary age deposited prior to rifting, are the presumably equivalent Galisteo and El Rito Formations. Three overlying units, deposited in response to local volcanism, are the Picuris and Abiquiu Tuffs, and the Bishops Lodge Member of the Tesuque Formation. These tuffaceous sediments are overlain by the major basin-fill deposits: the Tesuque and Chamita Formations of the restricted Santa Fe Group of Galusha and Blick (1971). In this report Santa Fe Group is used as defined by these authors. The youngest basin deposits are the fan-shaped Pliocene Ancha and Puye Formations (which are also part of the Santa Fe Group according to some authors). After their deposition, erosion dominated; and Pleistocene alluvial deposits are confined to erosional-surface gravels, terraces, and dune sands.

Eocene and Oligocene(?) Galisteo and El Rito Formations

The Galisteo and El Rito Formations (Stearns, 1943; Smith, 1938), the oldest Tertiary deposits in the Española basin, consist of sandstones, shales, and boulder conglomerates with red iron oxide staining. The Galisteo is exposed along the southern margin and in an upthrown block on the southeast edge of the Jemez Mountains (Smith and others, 1970). The El Rito Formation is exposed only in the northwest part of the basin. Both formations unconformably overlie Mesozoic rocks. The Galisteo Formation is conformably overlain by the Espinaso Formatio the El Rito Formation is unconformably overlain by the Abiquiu Tuff.

Stearns (1943) cited the Sangre de Cristo Mountains and the Nacimiento uplift as source areas for the Galisteo Formation. The Precambrian core of the Brazos uplift was the source for much of the El Rito Formation according to Bingler (1968).

Early to late Eocene and possibly Oligocene mammalian fossils are present in the Galisteo Formation (Galusha and Blick, 1971; Disbrow and Stoll, 1957; Robinson, 1957). Fossils have not been reported for the El Rito Formation, these two formations have been correlated solely on lithology.

Espinaso Volcanics

The Espinaso Volcanics, which overlies the Galisteo Formation south of the Española basin in the Santo Domingo subbasin, consists of volcaniclastic debris dated by K-Ar at 37 m.y. (Weber, 1971). Source areas (Stearns, 1953) have been dated by lead-alpha at 32-46 m.y. (Jaffe and others, 1959) for the Cerrillos Hills stock, and by K-Ar at 34 m.y. (Bachman and Mehnert, 1978) for the Ortiz Mountains. These dates provide a minimum age for the Galisteo Formation and a maximum age for possible Abiquiu Tuff deposits in the Cienega area.

Abiquiu and Picuris Tuffs

The Abiquiu Tuff (Smith, 1938), on the western side of the basin, and its probable correlative in the northeast part of the basin, the Picuris

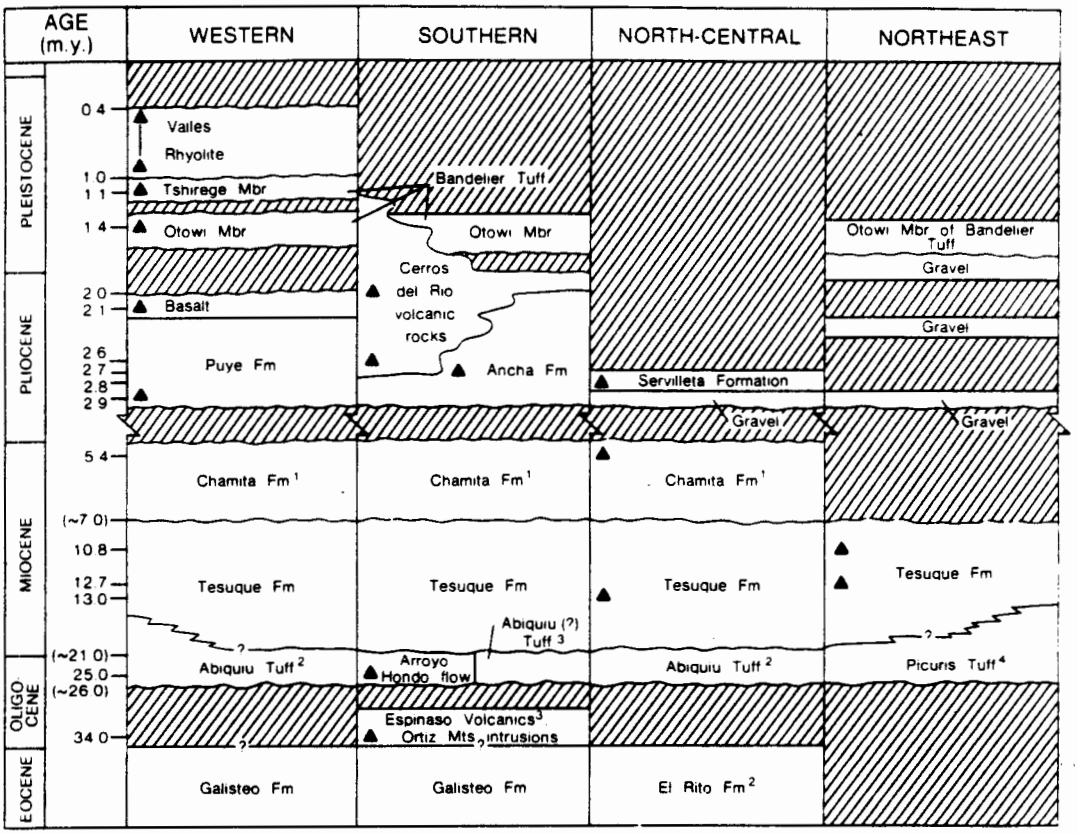

Fig. 3. Stratigraphic correlation chart for the Española basin, New Mexico. Radiometric age indicated by solid triangle. [1]Galusha and Blick, 1971; [2]Smith, 1938; [3]Stearns, 1943; [4]Cabot, 1938.

Tuff (Cabot, 1938), are tuffaceous sands and gravels containing numerous intermediate-composition volcanic clasts. Probable source areas for these tuffs were volcanic highlands to the north: the southern San Juan Mountains, the Ouesta volcanic center in the Sangre de Cristo Mountains, and the Taos Plateau. Pliocene basalts that cap the Taos Plateau have buried older intermediate-composition volcanic rocks (Lipman, this volume).

No paleontologic or radiometric ages have been published for either formation, but the ages of the source areas provide maximum ages. The Platoro caldera, at the northern end of the Brazos uplift, was active 27-30 m.y. ago (Lipman and others, 1970). Early activity on the Taos Plateau was 22-26 m.y. ago (Lipman, this volume). The Questa center was active about 23 m.y. ago (Laughlin and others, 1969). Also, the Abiquiu Tuff and the overlying Chama-el rito Member [sic] (Galusha and Blick, 1971) of the Tesuque Formation are in essence southern tongues of the volcaniclastic Los Pinos Formation (Butler, 1971; S. J. May, written commun., 1977). This formation interfingers with 5- to 26- m.y.-old basalt flows of the Hinsdale Formation along the eastern Brazos uplift and Taos Plateau (Lipman and Mehnert, 1975). The Abiquiu Tuff, as a southern tongue of the Los Pinos Formation, interfingers with Santa Fe Group sediments even though the majority of the Abiquiu in the type area is slightly older than the Santa Fe Group.

Further indications of age come from the southern end of the basin. In the Cienega area, possible Abiquiu Tuff overlies the Espinaso

Volcanics (Stearns, 1953) and several intermediate-composition volcanic rocks (Stearns, 1953; Sun and Baldwin, 1958) of probably mid-Oligocene age. Near Santa Fe a tuffaceous sand and siltstone with local tuff and volcanic conglomerate beds, called the Picuris Tuff (Cabot, 1938) or Bishops Lodge Member of the Tesuque Formation (Spiegel and Baldwin, 1963), disconformably underlie nonvolcaniclastic rocks (Boyer, 1959) and overlie an intermediate-composition flow with an age of 25 m.y. (Bachman and Mehnert, 1978). This flow may be related to volcanic activity at La Cienega, and all or part of the Bishops Lodge Member is equivalent to the Abiquiu(?) of Stearns (1953) at La Cienega and the type Abiquiu Tuff.

Los Pinos Formation

The Los Pinos Formation, exposed in the northwestern Española basin and north into the southern San Juan Mountains, is composed of volcaniclastic sandstones, conglomerates, and tuffs. The source area was largely the southern San Juan Mountains. There the Los Pinos Formation overlies 26-to 30-m.y.-old rocks and contains interbedded 4-to 26-m.y.-old basalt flows which were included in the Los Pinos by Butler (1971), but are correlative with basalt of the Hinsdale Formation (Lipman and Mehnert, 1975). The Los Pinos Formation is therefore late Oligocene to early Pliocene in age and equivalent to the Abiquiu and Picuris Tuffs in its basal part and to the Tesuque and Chamita Formations of the Santa Fe Group in its upper part.

Santa Fe Group

Sedimentary rocks of the Santa Fe Group, which overlie or interfinger with the Abiquiu and Picuris Tuffs, have been divided into the Tesuque and Chamita Formations by Galusha and Blick (1971). They further subdivided the Tesuque Formation into five members (fig. 4): Nambé, Skull Ridge, Pojoaque, Ojo Caliente Sandstone, and Chama-el rito. The Pojoaque and Chama-el rito Members are described as contemporaneous fans deposited in different areas of the Española basin from separate source areas. The Chama-el rito is exposed in the northwest portion of the basin and is the only member with dominantly volcanic-rock clasts. The volcanic detritus in the Chama-el rito Member indicates drainage southward from the Platoro, Taos, and Questa volcanic centers and suggests that this member is actually a tongue of the Los Pinos Formation. The other members contain predominantly Precambrian detritus derived from the Sangre de Cristo Mountains. Additional stratigraphic study of the Santa Fe Group is needed. The members defined by Galusha and Blick (1971) have neither been thoroughly described, nor has all of the basin been mapped.

My recent mapping in the northeast and northwest portions of the basin has led to the recognition of (1) young faulting (described below) that modifies the stratigraphic correlations across the basin (fig. 4); (2) volcaniclastic rocks in the northeast that are possibly equivalent to the Chama-el Rito; and (3) a major east-west drainage 10 m.y. old, for which a new unit was defined as the Cejita Member of the Tesuque Formation (Manley, 1976c and 1977).

The age of the Santa Fe Group of Galusha and Blick (1971) is fairly well established. Fossil ages for these rocks extend from Hemingfordian (∿21 m.y.) to Hemphillian (10-35 m.y.) land mammal ages (Wood and others, 1941; Woodburne and others, 1974; Davis, 1975; Evernden and Evernden, 1970; Berggren and Van Couvering, 1973). Dacitic ash in the Nambé Member yielded a questionable lead-alpha age of 18 m.y. (Jaffe and

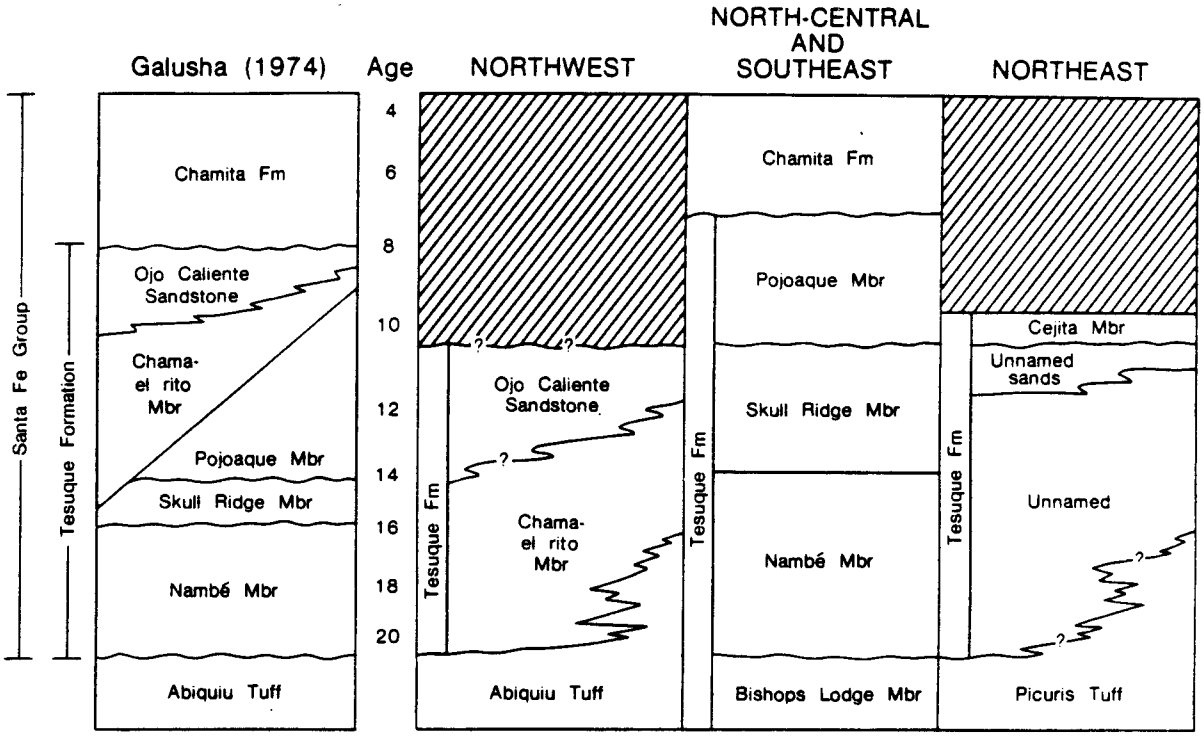

Fig. 4. Comparison of ages and nomenclature of Galusha (1974) and of this report.

others, 1959). Fission-track ages on zircons in tephra from the Skull Ridge and Pojoaque Members of the Tesuque Formation range from 14 to 9 m.y. (C. W. Naeser and G. A. Izett, written commun., 1976). New evidence indicates that the Chama-el rito and Ojo Caliente Sandstone Members have an age range of about 20-10 m.y. (fig. 4), which is older than Galusha (1974) suggested. This new evidence includes (1) lithologic similarity between these two units and unnamed Santa Fe Group deposits >11 m.y. old in the Picuris reentrant (Manley, 1976a); (2) presence of a graben in the central portion of the basin (Manley, 1978); and (3) K-Ar ages for dikes and flows in the Abiquiu reentrant (H. H. Mehnert, written commun., 1977 and 1978).

Two zircon fission-track ages from the Chamita Formation of Galusha and Blick (1971) are 5.2 and 5.4 m.y. (Manley, 1976c; MacFadden and Manley, 1976). Paleomagnetic data suggest a range of 4.5-6.0 m.y. for the exposed stratotype (MacFadden, 1977).

Post-Santa Fe Group Formations

Pliocene and Pleistocene sediments, which overlie the Santa Fe Group of Galusha and Blick (1971) with angular unconformity, include the Puye (Smith, 1938) and the Ancha Formations (Baltz and others, 1952). The Pliocene Puye and Ancha Formations, included in the Santa Fe Group by some authors, are fanglomerates derived from opposite sides of the basin. The Puye Formation, which also contains numerous laharic and pyroclastic deposits, was derived from the Jemez Mountains; the Ancha Formation source area was the Precambrian granitic and metamorphic rocks and pre-Tertiary sedimentary rocks of the Sangre de Cristo Mountains. The two formations interfinger with each other and with the volcanic

rocks of the Cerros del Rio volcanic field.

The contemporaneity of these units is also supported by radiometric ages: zircon fission-track ages of 2.9 m.y. and 2.7 m.y. for the Puye and Ancha Formations, respectively, (Manley, 1976a), and K-Ar ages of 2.8-<1.4 m.y. for the Cerros del Rio (Smith and others, 1970; Manley, 1976b; and Bachman and Mehnert, 1978). A flow overlying the type Ancha Formation is 2.0 m.y old. At the north end of the basin, an olivine tholeiite flow of the Servilleta Formation that unconformably overlies the Chamita Formation has a K-Ar age of 2.8 m.y.

Igneous Rocks of the Jemez Mountains

Volcanism began in the Jemez Mountains about 12 m.y. ago (Smith and Bailey, 1968). The west side of the Española basin was covered with volcanic rocks deposited first on the south and then to the north. Published K-Ar ages range from 9.1 to 0.43 m.y. (Bailey and others, 1969).

Faults

If the Española basin is a rift basin or graben, prominent boundary faults or fault systems should exist on at least one side. Several maps indicate boundary faults (Cabot, 1938; Kelley, 1956), and faults within the basin have been mapped by Smith (1938), Smith and others (1970), Galusha and Blick (1971), and Manley (1977).

Basin Boundary Faults

The eastern margin of the Española basin appears to lack a border fault. The Pecos-Picuris fault, which formed the eastern margin of th Uncompahgre highland in late Paleozoic time (Sutherland, 1972), has b considered by some to be a boundary fault, but this fault had right-lateral, strike-slip motion followed by down-to-the-east motion (Miller and others, 1963). Faults mapped west of the Pecos-Picuris fault by Cabot (1938) and Spiegel and Baldwin (1963) predate the Santa Fe Group (Galusha and Blick, 1971, p. 104). Post-Santa Fe faults along the eastern margin have mostly small, down-to-the-east displacements (K. Manley; E. H. Baltz, unpub. mapping). The gentle gravity-anomaly gradients of the eastern border, much gentler than for the eastern, fault-controlled border of the Albuquerque-Belen basin (Cordell, 1976), imply that the border either is a series of step-faults or is a tilted onlap without fault control. If step-faults are present in the basement rocks, it is surprising that they are not better expressed in the Santa Fe Group. In many locations sediments of the Santa Fe Group lap onto older rocks. The present western slope of the Sangre de Cristo Mountains above the basin fill may be a stripped surface. Its dip is approximately 70 m/km, which, if projected into the basin, would indicate 1,200 m of sedimentary rocks beneath the town of Española. With at least 360 m of downdropping in the central Velarde graben (discussed below), the total fill would be roughly 1,550 m compared to a minimum of 2,150 m calculated from gravity data (Cordell, 1976, p. 67).

The western margin of the Española basin is a northeast-trending zone of down-to-the-east faulting largely concealed by the Jemez volcanic field. North and south of the Jemez Mountains, rocks of the Santa Fe Group are faulted against Mesozoic rocks, and deposits of Permian to Quaternary age have been displaced (Smith and others, 1970).

Intra-basin Faults

Numerous high-angle, normal faults cut the Santa Fe Group in the eastern half of the basin. Most are less than 3 km long and displaced less than 90 m. The faults with east side down are more numerous, but those with west side down are usually larger (Galusha and Blick, 1971, p. 101). Most faults strike northward, subparallel to the strike of beds; but, near the western margin of the basin, the intra-basin faults tend to parallel the northeast trend of the boundary fault zone. To the north, this zone intersects the northwest-southeast faults that bound the Precambrian uplifts near La Madera and form the northern margin of the basin.

The Velarde Graben

The Velarde graben is an 8 km wide, central graben at the northern end of the Española basin. It appears as a pronounced gravity low (Cordell, 1976) coincident with an area that experienced 4.9 cm of relative subsidence between 1934 and 1939 (Reilinger and others, 1978). The Velarde graben appears to continue southwestward to the southern end of the basin and controls the position of the Rio Grande, which parallels the eastern margin of the graben. Large slump blocks of basalt-capped Chamita Formation that flank the eastern side of Black Mesa are probably in part a reflection of the underlying graben structure.

The east boundary of the Velarde graben is defined by the prominent Velarde fault, which extends along the western edge of the Picuris reentrant; a probable parallel fault is 0.8 km to the northwest at the margin of the Rio Grande flood plain (Manley, 1977). Stratigraphic relationships indicate a combined total displacement on both faults of >300 m down to the west. A third fault drops the basalt of La Mesita (northeast of Velarde) down to the west about 60 m. These faults are a southward continuation of the fault zone on the northwest side of the Picuris Range (Miller and others, 1963).

The western boundary of the Velarde graben is defined by faults beneath Black Mesa. The major fault, extending southward from Black Mesa, is a high-angle, normal fault downdropped to the east that places the Chamita Formation on the east against the Ojo Caliente Sandstone Member of the Tesuque Formation.

Another major zone of faulting, northwest of Black Mesa and west of and subparallel to the Rio Ojo Caliente, shows a displacement down to the west (Galusha and Blick, 1971); however, the entire eastern block is rotated downward to the east. This motion may have been a response to the formation of the Velarde graben. The trend of this fault zone is subparallel to the fault zones beneath Black Mesa and within the central part of the basin.

As the Velarde graben continues southward, the western margin passes across the Pajarito Plateau as the Pajarito fault zone, which juxtaposes the Pleistocene Bandelier Tuff against the Eocene and Oligocene(?) Galisteo Formation. These western margin faults are shown by Galusha and Blick (1971) and Smith and others (1970).

South of Española, the eastern boundary of the Velarde graben is partly obscured by the broad flood plains of the Rio Grande, Santa Cruz River, and Pojoaque River. Prominent north-south faults of unknown displacement are present in this part of the basin. The boundary here may be a series of small faults and rotated blocks characteristic of a tensional environment.

At the southern end of the Española basin, the Cerros del Rio volcanic field conceals the structural relationships; however, the presence of a

central graben may be inferred from faulting and from the thickness of the Ancha Formation. The Pajarito fault is present to the west; near the Rio Grande the Pliocene Ancha Formation is 200 m thick but it thins abruptly to the east where, in spite of poor exposures, a few north-trending faults could be mapped (Spiegel and Baldwin, 1963, p. 76). A northeast-trending zone of well-cemented sandstone blocks, thought to be Pennsylvanian(?) quartzites by Spiegel and Baldwin (1963, p. 77-78), are actually the result of cementation along another graben border fault. The graben at this end of the basin has widened to roughly 30 km.

Geologic History

Laramide orogeny resulted in uplift of the Precambrian-cored ranges of north-central New Mexico (Woodward, 1974), including the Nacimiento uplift and Sangre de Cristo Mountains. During early Eocene they were partially stripped of Mesozoic and older sedimentary rocks (Baltz, 1967). Low areas to the east and south of these uplifts, filled by the Galisteo and El Rito Formations, were not the same configuration as the later rift basins (Stearns, 1953). Paleocurrent and provenance studies would contribute greatly to the understanding of these formations and their depositional basins. Near the close of the Eocene, the area was probably one of low relief with a broad erosion surface similar to that in southern Colorado (Scott, 1975). The interval of erosion may correlate with that observed by Stearns (1953) as preceding deposition of his Abiquiu(?) Formation at the southern end of the Española basin. In early Oligocene, intermediate-composition volcanism began at the Cerrillos Hills and the Ortiz Mountains, and in the southern San Juan Mountains. In the San Juan Mountains, rocks were tilted eastward and beveled during late Oligocene deposition of the Los Pinos Formation (Lipman and Mehnert, 1975) as the Rio Grande rift began to form.

Direct evidence of initiation of rifting is not available from the Española basin, but the Abiquiu and Picuris Tuffs, if deposited during early rifting, can be traced to 22- to 30- m.y.- old source areas. Regional extension began about 29 m.y. ago in the Socorro-Magdalena area (Chapin and Seager, 1975); rifting was in progress by 26 m.y. ago in southern New Mexico (Seager and Clemons, 1975) and in southern Colorado (Lipman and Mehnert, 1975).

Deposition of the Los Pinos Formation and Abiquiu and Picuris Tuffs was not confined to the present Española basin, but extended west to the eastern flank of the Nacimiento uplift and north onto the Brazos uplift. Relief was probably still low (Denny, 1940; Stearns, 1953; Church and Hack, 1939), although angular, poorly sorted gravel in the basal Abiquiu Tuff from a Precambrian source to the north or west may reflect the earliest extensional tilting and fragmentation in the Española basin. Drainage directions were generally southward into a seasonal lake near the southern margin of the basin (Stearns, 1953), but paleodrainage has not been fully studied.

The Sangre de Cristo Mountains emerged as a source area for the lower Tesuque Formation (Nambé Member) during the early Miocene. The Chama-el rito Member in the northwest and the unnamed Santa Fe Group deposits (fig. 4) in the northeast, which had source areas in both the Sangre de Cristo Mountains and southern San Juan Mountains, extended beyond the present rift borders. The western boundary faults have offset the earliest Santa Fe Group deposits as much as 320 m, but absence of coarse fanglomerates indicates that the boundary faults developed after deposition.

As early Miocene deposition continued, the proportion of intermediate-composition volcanic detritus entering the basin decreased, especially

at the southern end. In mid-Miocene, basaltic volcanism occurred along north-south faults north of the present Jemez Mountains. Flows interbedded with the Cham-el rito Member and dikes crosscutting the Abiquiu Tuff range from 13 to 9 m.y. in age (H. H. Mehnert, written commun., 1977. These eruptions indicate the onset of volcanism that culminated in the accumulation of the Jemez volcanic field. They may also indicate the initiation of faulting which produced the present western boundary in the Española basin.

Also in mid-Miocene a major stream in the northern part of the basin flowed westward from the Sangre de Cristo Mountains through the Picuris reentrant (Manley, 1974; 1976c). Coarse, well-rounded gravel of Precambrian and Paleozoic clasts in the Cejita Member of the Tesuque Formation implies considerable positive relief within the Sangre de Cristo Mountains. The stream may have terminated in a closed-basin lake or it may have flowed into the San Juan basin, but no deposits of the appropriate age are exposed in either the Santo Domingo subbasin or San Juan basin. In the Albuquerque-Belen basin, correlative deposits (lower or Miocene part of Cochiti Formation) give no indication of a major stream.

The upper Miocene Chamita Formation was deposited by westward-flowing streams, but the major mid-Miocene stream had become less competent and more braided, and the axis of the basin appears to have shifted eastward as the basin filled.

The Velarde graben formed in early Pliocene. Motion along its boundary faults may have begun in the late Miocene, but between 5 and 3 m.y. ago the Chamita Formation was displaced at least 300 m. Thereafter the entire basin underwent erosion that removed the Chamita Formation from highlands and preserved it primarily within the graben.

Renewed tectonism in the late Pliocene is implied by deposition of the Puye and Ancha Formations and by volcanism on the Taos Plateau and in the Cerros del Rio. Continued downdropping of the Velarde graben resulted in thick accumulations of the Puye and Ancha Formations within the graben. Outside the graben these formations were subject to continual regrading. Lava flows in the Cerros del Rio field periodically dammed the Rio Grande, causing changes in its course; at least once, flows created a large lake that filled much of the basin and deposited the Culebra Lake Clay of Kelley (1956). A basalt flow that entered the lake has an age of 2.1 m.y. (R. L. Smith, written commun., 1974).

In the Pleistocene, erosion dominated except for the eruption of the Bandelier Tuff. The basin was excavated to its present configuration with only a few standstills that allowed for the formation of minor erosional surfaces. Velarde graben faults were still active: the Pajarito fault offset the 1.1-m.y.-old Tshirege Member of the Bandelier Tuff (Smith and others, 1970; Doell and others, 1968) and several earthquake epicenters in the last decade were plotted near the Pajarito fault (Jiracek, 1974).

Age of the Rio Grande

The Rio Grande follows the rift from the San Luis basin in southern Colorado to Mexico. Because it connects the structural basins of the rift, its inception as a through-going drainage is significant to rift development. In the Española basin the Rio Grande became established 3-5 m.y. ago, in conjunction with mid-Pliocene basinwide erosion. Coarse, well-rounded gravels with lithologies from outside the basin unconformably overlie the Chamita Formation at the base of the Puye Formation (Totavi Lentil of Griggs, 1964) and below the Servilleta basalt on Black Mesa. A zircon fission-track age from a pumice bed

immediately above the Totavi Lentil is 2.9 m.y. (Manley, 1976a), and the Servilleta flow has a K-Ar age of 2.8 m.y. (Manley, 1976b). The Chamita Formation ages of 5.2 and 5.6 m.y. provide a maximum age control.

Relation To Other Rift Basins

The symmetry of the Española basin differs from that of adjacent basins. Both the San Luis and Albuquerque-Belen basins have faulted eastern margins with a vertical stratigraphic separation of perhaps as much as 5 km (Kelley and Northrop, 1975; Davis and others, 1978). The geometry of basin-fill deposits suggests that both basins developed from eastward tilting of structural blocks, in contrast to the westward tilting in the Española basin. This difference may be related to the presence of discrete crustal blocks which have responded to tension by rotational downdropping rather than by simple vertical displacement.

New radiometric ages make it possible to compare the histories of different areas along the rift. Events from southern Colorado to southern New Mexico show some interesting similarities. Following late Eocene erosion, intermediate-composition volcanism occurred in the early Oligocene (37 to 30 m.y. ago) in the Las Cruces area (Clemons and Seager, 1973), the Socorro area (Chapin and Seager, 1975), the Santo Domingo subbasin (Bachman and Mehnert, 1978; Weber, 1971; Jaffe and others, 1959), and in the San Juan Mountains (Lipman and others, 1970). Extensional faulting began about 29 m.y. ago in the Socorro area (Chapin and Seager, 1975) and 26 m.y. ago in the southern San Juans (Lipman and Mehnert, 1975). Upper Oligocene volcaniclastic rocks were deposited in partially developed basins. Ages for the onset of deposition cluster at 26 m.y. (Lipman and Mehnert, 1975; Bachman and Mehnert, 1978; Manley, unpub. data, 1976; Machette, 1978; Lipman and Mehnert, 1978, written commun.; Clemons and Seager, 1973). Chapin and Seager (1975) stated that the volcanism between 26 and 20 m.y. ago in the Socorro area was basaltic andesites. In the Cienega area, latites monzonite, andesite, and basalt were erupted (Sun and Baldwin, 1958). Basalts and rhyolites were more common in the southern San Juan Mountains (Lipman and others, 1970).

Several Miocene events are comparable from northern and southern ends of the rift. The volcanic quiescence between 20 and 14 m.y. ago in southern New Mexico may be reflected in the Española basin by the nontuffaceous Nambé Member of the Tesuque Formation. About 12-14 m.y. ago, volcanic activity increased: rhyolites were erupted in the Socorro area (Magdalena Peak, Strawberry Peak, and Socorro Peak) and the Jemez volcanic field began. Somewhat after 9 m.y. ago, deformation increased markedly. The Socorro area was block faulted, the Rincon Valley Formation of Hawley (1970), containing the 9-m.y.-old Selden Basalt Tongue (Chapin and Seager, 1975), was tilted and beveled; and the Popotosa Formation, containing a 9-m.y.-old basalt in its upper part (Machette, 1978), was tilted and beveled.

In latest Miocene, major deformation continued or occurred again. Paleobasins in the southern part of the state were disrupted (Chapin and Seager, 1975) and the Velarde graben formed. An erosional period from roughly 4 to 3 m.y. ago affected the entire rift. During this period a number of broad, penecontemporaneous erosion surfaces formed; one of these was the Ortiz surface (Bryan and McCann, 1938). After this erosional period, a number of formations and basalt flows were deposited, including the Camp Rice (of Strain, 1969), Sierra Ladrones, Puye, Ancha, and Servilleta Formations and the flows of Mesa Prieta, Santa Ana Mesa (Armstrong and others, 1976), Isleta volcano and Cantilon Hill (Kudo and others, 1977), Chivato Mesa (P. W. Lipman and H. H.

Mehnert, written commun., 1978), and the Cerros del Rio field (Manley, 1976b; Bachman and Mehnert, 1978).

The initiation of the Rio Grande as a through-going drainage in the Española basin is established as late Pliocene. Evidence from other basins supports a similar age. River gravels are present beneath Santa Ana Mesa and interfinger with Cerros del Rio flows. The oldest age control at present is provided by a 4 m.y.-old basalt (Bachman and Mehnert, 1978) that overlies gravels of the Rio Grande in the Sierra Ladrones Formation.

References

Armstrong, R. L., R. C. Speed, W. C. Graustein, and A. Y. Young, K-Ar dates from Arizona, Montana, Nevada, Utah, and Wyoming, Ischron/West, 16, 1-5, 1976.

Aubele, J. C., Geology of Cerros del Rio volcanic field, New Mexico Bur. Mines and Mineral Resources Circ., 163, 198-201, 1978.

Bachman, G. O., and H. H. Mehnert, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico, Geol. Soc. Amer. Bull., 89, 283-292, 1978.

Bailey, R. A., R. L. Smith, and C. S. Ross, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico, U.S. Geol. Survey Bull., 1274-P, 19 pp., 1969.

Baltz, E. H., Stratigraphy and regional tectonic implications of part of upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico, U.S. Geol. Survey Prof. Paper, 552, 101 pp., 1967.

Baltz, E. H., Jr., G. H. Dixon, R. L. Griggs, R. B. Johnson, Z. Spiegel, and G. H. Wood, First day's road log, New Mexico Geol. Soc. Guidebook, 3, 12-33, 1952.

Berggren, W. A., and J. Van Couvering, Late Neogene chronostratigraphy biostratigraphy, biochronology, and paleoclimatology, Woods Hole Oceanographic Institution Technical Report WHOI-73-40, Woods Hole, Massachusetts, 352 pp., 1973.

Bingler, E. C., Geology and mineral resources of Rio Arriba County, New Mexico, New Mexico Bur. Mines and Mineral Resources Bull., 91, 158 pp., 1968.

Boyer, W. W., Playa deposit in the Bishops Lodge Member of the Tesuque Formation, Santa Fe County, New Mexico, Jour. Sed. Petrol., 29, 64-72, 1959.

Bryan, K., and F. T. McCann, The Ceja del Rio Puerco--a border feature of the Basin and Range Province in New Mexico, Part II, Geomorphology, Jour. Geol., 46, 1-16, 1938.

Butler, A. P., Jr., Tertiary volcanic stratigraphy of the eastern Tusas Mountains, southwest of the San Luis Valley, Colorado-New Mexico, New Mexico Geol. Soc. Guidebook, 22, 289-300, 1971.

Cabot, E. C., Fault border of the Sangre de Cristo Mountains north of Santa Fe, New Mexico, Jour. Geol., 46, 88-105, 1938.

Chapin, C. E., The Rio Grande rift; Part 1, Modifications and additions, New Mexico Geol. Soc. Guidebook, 22, 191-201, 1971.

Chapin, C. E., and W. R. Seager, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas, New Mexico Geol. Soc. Guidebook, 26, 297-321, 1975.

Church, F., and J. T. Hack, An exhumed erosion surface in the Jemez Mountains, New Mexico, Jour. Geol., 47, 613-629, 1939.

Clemons, R. E., and W. R. Seager, Geology of Souse Springs quadrangle, New Mexico, New Mexico Bur. Mines and Mineral Resources Bull., 100, 31 pp., 1973.

Cordell, L., Aeromagnetic and gravity studies of the Rio Grande graben

in New Mexico between Belen and Pilar, New Mexico Geol. Soc. Spec. Pub., 6, 62-70, 1976.

Cordell, L., Regional Geophysical setting of the Rio Grande rift, Ge Soc. Amer. Bull., 89, 1073-1090, 1978.

Davis, A. M., Tertiary faunas, American Elsevier Pub. Co., New York, 447 pp., 1975.

Davis, G. H., G. R. Keller, and L. Cordell, A tectonic study of the San Luis basin, Colorado, using gravity data, 1978 International Symposium on the Rio Grande rift, Program and Abstracts, Los Alamos Scientific Laboratory LA-7487-C, 29, 1978.

Denny, C. S., Santa Fe Formation in the Española Valley, New Mexico, Geol. Soc. Amer. Bull., 51, 677-694, 1940.

Disbrow, A. E., and W. C. Stoll, Geology of the Cerrillos area, Santa Fe County, New Mexico, New Mexico Bur. Mines and Mineral Resources Bull., 48, 73 pp., 1957.

Doell, R. R., G. B. Dalrymple, R. L. Smith, and R. A. Bailey, Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles caldera, New Mexico, Geol. Soc. Amer. Mem., 116, 211-248, 1968.

Evernden, J. F.,and R. K. S. Evernden, The Cenozoic time scale, Geol. Soc. Amer. Spec. Paper, 124, 71-90, 1970.

Galusha, T., Dating rocks of the Santa Fe Group--programs and problems, New Mexico Geol. Soc. Guidebook, 25, 283-286, 1974.

Galusha, T., and J. C. Blick, Stratigraphy of the Santa Fe Group, New Mexico, Amer. Mus. Nat. Hist. Bull., 144, 127 pp., 1971.

Griggs, R. L., Geology and ground-water resources of the Los Alamos area, New Mexico, U.S. Geol. Survey Water-Supply Paper, 1753, 107 pp., 1964.

Hawley, J. W., Cenozoic stratigraphy of the Rio Grande valley area, Doña Ana County, New Mexico, El Paso Geol. Soc. Guidebook, 4, 24-27, 1970.

Jaffe, H. W., D. Gottfried, C. L. Waring, and H. W. Worthing, Lead-alpha age determinations of accessory minerals of igneous rocks (1953-19 U.S. Geol. Survey Bull., 1097-B, 65-148, 1959.

Jiracek, G. R., Geophysical studies in the Jemez Mountains region, New Mexico, New Mexico Geol. Soc. Guidebook, 25, 137-144, 1974.

Kelley, V. C., The Rio Grande depression from Taos to Santa Fe, New Mexico Geol. Soc. Guidebook, 7, 109-114, 1956.

Kelley, V. C., and S. A. Northrop, Geology of Sandia Mountains and vicinity, New Mexico, New Mexico Bur. Mines and Mineral Resources Mem., 29, 136 pp., 1975.

Kudo, A. M., V. C. Kelley, P. E. Damon, and M. Shafiqullah, K-Ar ages of basalt flows at Canjilon Hill, Isleta volcano, and the Cat Hills volcanic field, Albuquerque-Belen Basin, central New Mexico, Isochron/West, 18, 15-16, 1977.

Laughlin, A. W., W. A. Rehrig, and R. L. Mauger, K-Ar chronology and sulfur and strontium isotope ratios at the Questa Mine, New Mexico, Econ. Geol., 64, 903-909, 1969.

Lipman, P. W., T. A. Steven, and H. H. Mehnert, Volcanic history of the San Juan Mountains, Colorado, as indicated by K-Ar dating, Geol. Soc. Amer. Bull., 81, 2329-2352, 1970.

Lipman, P. W., and H. H. Mehnert, Late Cenozoic basalt volcanism and development of the Rio Grande depression in the Southern Rocky Mountains, Geol. Soc. Amer. Mem., 116, 119-154, 1975.

MacFadden, B. J., Magnetic polarity stratigraphy of the Chamita Formation stratotype (Mio-Pliocene) of north-central New Mexico, Amer. Jour. Sci., 277, 769-800, 1977.

MacFadden, B. J., and K. Manley, Magnetic stratigraphy,

tephrochronology, and mammalian biostratigraphy of the type Chamita Formation, north-central New Mexico, Geol. Soc. Amer. Abstr. with Programs, 8, 605, 1976.

Machette, M. N., Geologic map of the San Acacia quadrangle, Socorro County, New Mexico, U.S. Geol. Survey Geol. Quad. Map, GQ-1415, 1978.

Manley, K., Late Cenozoic history of the Española Basin, New Mexico, Geol. Soc. Amer. Abstr. with Programs, 6, 213, 1974.

Manley, K., Tephrochronology of the Tesuque, Ancha, and Puye Formations of the Santa Fe Group, Española Basin, New Mexico, Geol. Soc. Amer. Abstr. with Programs, 8, 606-607, 1976a.

Manley, K., K-Ar age determinations on Pliocene basalts from the Española Basin, New Mexico, Isochron/West, 16, 29-30, 1976b.

Manley, K., The late Cenozoic history of the Española Basin, New Mexico, University of Colorado Ph.D. dissertation, 171 pp., 1976c.

Manley, K., Geologic map of the Cejita Member (new name) of the Tesuque Formation, Española Basin, New Mexico, U.S. Geol. Survey Misc. Field Studies Map, MF-877, 1977.

Manley, K., Pliocene deformation along the Rio Grande rift in the Española basin, New Mexico, Geol. Soc. Amer. Abstr. with Programs, 10, 233, 1978.

Manley, K., and C. W. Naeser, Fission-track ages for tephra layers in upper Cenozoic rocks, Española Basin, New Mexico, Isochron/West, 18, 13-14, 1977.

Miller, J. P., A. Montgomery, and P. K. Sutherland, Geology of part of the southern Sangre de Cristo Mountains, New Mexico, New Mexico Bur. Mines and Mineral Resources Mem., 11, 106 pp., 1963.

Reilinger, R. E., L. D. Brown, J. E. Oliver, and J. E. York, Recent vertical crustal movements in the Rio Grande rift from leveling observations, 1978 International Symposium on the Rio Grande rift, Program and Abstracts, Los Alamos Scientific Laboratory LA-7487-C, 73-74, 1978.

Robinson, P., Age of Galisteo Formation, Santa Fe County, New Mexico, Amer. Assoc. Petrol. Geol. Bull., 4, 757, 1957.

Scott, G. R., Cenozoic surfaces and deposits in the southern Rocky Mountains, Geol. Soc. Amer. Mem., 144, 227-248, 1975.

Seager, W. R., and R. E. Clemons, Geology of the Cedar Hills-Selden Hills, Doña Ana County, New Mexico, New Mexico Bur. Mines and Mineral Resources Circ., 133, 23 pp., 1975.

Smith, H. T. U., Tertiary geology of the Abiquiu quadrangle, New Mexico, Jour. of Geol., 46, 933-965, 1938.

Smith, R. L., and R. A. Bailey, Stratigraphy, structure, and volcanic evolution of the Jemez Mountains, New Mexico, Quat. Colorado School of Mines, 63, 259-260, 1968.

Smith, R. L., R. A. Bailey, and C. S. Ross, Geologic map of the Jemez Mountains, New Mexico, U.S. Geol. Survey Misc. Geol. Inv. Map, I-571, 1970.

Spiegel, Z., and B. Baldwin, Geology and water resources of the Santa Fe area, New Mexico, U.S. Geol. Survey Water-Supply Paper, 1525, 258 pp., 1963.

Stearns, C. E., The Galisteo Formation of north-central New Mexico, Jour. Geol., 51, 301-319, 1943.

Stearns, C. E., Tertiary geology of the Galisteo-Tongue area, New Mexico, Geol. Soc. Amer. Bull., 64, 459-508, 1953.

Strain, W. S., Late Cenozoic strata of the El Paso-Juarez area, New Mexico Geol. Soc. Guidebook, 20, 155-157, 1969.

Sun, M. and B. Baldwin, Volcanic rocks of the Cienega area, Santa Fe County, New Mexico, New Mexico Bur. Mines and Mineral Resources Bull., 54, 80 pp., 1958.

Sutherland, P. K., Pennsylvanian stratigraphy, southern Sangre de Cristo Mountains, New Mexico, in, Mallory, W. W., ed., Geologic atlas of the Rocky Mountain region, Hirschfeld Press, Denver, 139-142, 1972.

Weber, R. H., K-Ar ages of Tertiary igneous rocks in central and wester New Mexico, Isochron/West, 71, 33-45, 1971.

Wood, H. E., II, R. W. Chaney, J. Clark, E. H. Colbert, G. L. Jepsen, J. B. Reeside, Jr., and C. Stock, Nomenclature and correlation of the North American continental Tertiary, Geol. Soc. Amer. Bull., 52, 1-48, 1941.

Woodburne, M. O., R. H. Tedford, M. S. Stevens, and B. E. Taylor, Early Miocene mammalian faunas, Mojave Desert, California, Jour. Paleon., 48, 6-26, 1974.

Woodward, L. A., Tectonics of central-northern New Mexico, New Mexico Geol. Soc. Guidebook, 25, 123-129, 1974.